Department of Energy, National Energy Technology Laboratory, Power Plant-Water R&D Program

Barbara Carney*, Thomas Feeley, and Andrea McNemar
U.S. Department of Energy/National Energy Technology Laboratory

*barbara.carney@netl.doe.gov

INTRODUCTION

Thermoelectric power generation requires large volumes of fresh water, mostly used to cool and condense the steam after it exits the turbine, ranking just behind irrigation/agriculture in total freshwater withdrawal. A Department of Energy/National Energy Technology Laboratory (DOE/NETL) analysis suggests that in 2005 the thermoelectric power generation sector withdrew and consumed 147 billion gallons per day (bgd) and 3.7 bgd of freshwater, respectively. The vast amount of water used for electrical power generation makes this energy/water connection the largest. NETL is researching methods to decrease the impact of electrical power production on water resources.

Water Requirements for Thermoelectric Generation

Most of the demand for water in thermoelectric plants is for cooling water for condensing steam. Thermoelectric power production is the conversion of thermal energy into electrical energy. This is done in two ways, the Brayton cycle and the Rankine Cycle. In the Brayton cycle, fuel and a compressor are used to heat and increase the pressure of a gas which is then expanded over a turbine. The turbine blades spin, which spins the generator, a coiled wire cylinder which spins in a magnetic field to generate electricity. In the Rankine cycle (or steam cycle), fuel is used to heat a liquid to produce a high pressure gas (usually water is heated to produce steam), which is expanded over a turbine to produce electricity. The driving force for the process is the phase change of the gas to a liquid following the turbine, and this is where the demand for cooling water arises. A vacuum is created in the condensation process which draws the gas over the turbine. This low pressure is critical to the thermodynamic efficiency of the process. An increased backpressure will lower the efficiency of the process. When the Brayton cycle is used, the gas passing over the turbine still has significant thermal energy and is used as a heat source for the steam cycle and this is called a combined cycle. The Brayton cycle can only be used with very clean fuels such as natural gas or synthetic gas from coal or biomass gasification. Otherwise, the turbine blades will be damaged.

Thermoelectric generation relies on a fuel source (fossil, nuclear, biomass, geothermal, or sun) to heat the fluid to drive a turbine. If natural gas is used, a combined cycle is used and it is called natural gas combined cycle (NGCC) and this is the most efficient way to generate electricity. If coal gasification is use to produce synthetic gas, it is called integrated gasification combined cycle (IGCC). This is the second most efficient generation method. If coal is used, a boiler is needed to transfer heat from the combustion of the coal to water. There are many boiler designs, but for electricity generation, the coal is pulverized into a fine powder and fed as a slurry into the boiler, this is called pulverized coal (PC) combustion. The higher the temperature and pressure of the steam, the more efficient the conversion process is, with supercritical being the high temperature/pressure process and subcritical not as efficient. For nuclear reactors, the nuclear fuel is the heat source and the steam remains below subcritical pressures and is less efficient than PC plants. Other sources of heat are geothermal and concentrating solar power plants. If the operating temperature is not high enough to boil water, another working fluid such as ammonia or an organic such as propane is used. In all cases of thermoelectric power generation, condensation of the gas to a liquid after the turbine is a critical part of the process and affects the efficiency of the process. The more efficient the process of converting thermal energy to electrical energy, the less water is required per kilowatt hour (kWhr).

The steam condensation typically occurs in a shell-and-tube heat exchanger known as a condenser. The steam is condensed on the shell side by the flow of cooling water through tube bundles located within the condenser. Cooling water mass flow rates of greater than 50 times the steam mass flow rate are necessary depending on the allowable temperature rise of the cooling water, typically 15-25ºF. The design and operating parameters of the cooling system are critical to the overall power generation efficiency. At higher condenser cooling water inlet temperatures, the steam condensate temperature is higher and subsequently turbine backpressure is higher. The turbine backpressure is inversely related to power generation efficiency: the higher the turbine backpressure, the lower the power generation efficiency.

There are three general types of cooling system designs used for thermoelectric power plants: once-through, wet recirculating, and dry. In once-through systems, the cooling water is withdrawn from a local body of water such as a lake, river, or ocean and the warmer cooling water is subsequently discharged back to the same water body after passing through the surface condenser. As a result, plants equipped with once-through cooling water systems have relatively high water withdrawal, but low water consumption.

There are two primary technologies used to support wet recirculating cooling systems – wet cooling towers and cooling ponds. The most common type of recirculating system uses wet cooling towers to dissipate the heat from the cooling water to the atmosphere. In wet recirculating systems, warmed cooling water is pumped from the steam condenser to a cooling tower. The cooling tower consists of a large tower with packing that allows contact of the warm water with air. The heat from the warm water is transferred to ambient air flowing through the cooling tower. In the process, a portion of the warm water evaporates from the cooling tower and forms a water vapor plume. The latent heat required for the water to convert from a liquid to a vapor is responsible for most of the cooling in the tower. The plume leaving the tower can be cooler than the ambient temperature due to heat loss in this phase change. The cooled water is then recycled back to the condenser. Because clean water is evaporated and salts and minerals remain behind, a portion of the cooling water needs to be discharged from the system – known as blowdown − to prevent the buildup of minerals and sediment in the water that could adversely affect performance. The quantity of blowdown required for a particular cooling water system is determined by a parameter known as “cycles of concentration”, which is defined as the ratio of dissolved solids in the circulating water to that in the makeup water. As the cycles of concentration increase, the quantity of blowdown and makeup water decreases. For a wet recirculating system, makeup water needs to be withdrawn from the local water body to replace water lost through evaporation and blowdown. As a result, plants equipped with wet recirculating systems have relatively low water withdrawal, but high water consumption, compared to once-through systems.

Wet cooling towers are available in two basic designs – mechanical draft and natural draft. Mechanical draft towers utilize a fan to move ambient air through the tower, while natural draft towers rely on the difference in air density between the warm air in the tower and the cooler ambient air outside the tower to draw the air up through the tower. In both designs, the warm cooling water is discharged into the tower for direct contact with the ambient air. A cooling pond serves the same purpose as a wet cooling tower, but relies on natural conduction/convection heat transfer from the water to the atmosphere as well as evaporation to cool the recirculating water.

Dry cooling systems can use either a direct or indirect air cooling process. In direct dry cooling, the turbine exhaust steam flows through tubes of an air-cooled condenser (ACC) where the steam is cooled directly via conductive heat transfer using a high flow rate of ambient air that is blown by fans across the outside surface of the tubes. Therefore, cooling water is not used in the direct air-cooled system. For indirect dry cooling (also known as a Heller system), a conventional water-cooled surface condenser is used to condense the turbine exhaust steam, but a dry cooling tower, similar in design to an ACC, is used to conductively transfer the heat from the water to the ambient air. As a result, there is no evaporative loss of cooling water with an indirect dry cooling system and both water withdrawal and consumption are minimal. Just as with a wet cooling tower, the dry cooling tower can be either mechanical draft or natural draft. Mechanical draft requires a fan and parasitic power to run it, but natural draft towers have to be larger and require more capital expenditure to build.

In the United States, existing thermoelectric power plants use each of these types of systems, with estimates indicating that 43% of generating capacity is once-through, 42% wet recirculating, 0.9% dry cooling, and 14% cooling ponds.

Historically, power plants were located on large rivers and used once through cooling. This is the most economical both with respect to capital required (a water intake structure) and efficiency of electrical generation. However, there are environmental impacts on the water due to cooling use, including entrapment of small organisms which are damaged going through pumps, and entrainment of larger fish in the intake screens. The thermal discharge can also harm a water body, especially by lowering the oxygen content of the water. The use of cooling towers is likely to become much more pronounced in the future due to the Clean Water Act 316(b) provisions. Although once-through cooling systems can still be legally permitted under 316(b), the complexity of the permitting, analysis and reporting requirements may discourage their use.

Projections of Future Thermoelectric Capacity and Generation

The EIA publishes its *Annual Energy Outlook* (AEO) to provide a forecast as to where the energy sector will be in the future, including projections of thermoelectric capacity and generation. AEO 2008 projections of capacity and generation to 2030 were used to calculate future thermoelectric generation water withdrawal and consumption. Coal-fired generating capacity, including IGCC, is projected to increase by 96 GW from 2005 to 2030.

Projection of Water Needs for Future Thermoelectric Generation

NETL did an analysis that projects that by 2030, average daily national freshwater withdrawals required to meet the needs of U.S. thermoelectric power generation could range from 112 BGD to 154 BGD depending upon case assumptions. The 2005 baseline value of 146 BGD compares fairly closely to the USGS estimates that thermoelectric power plants withdrew approximately 132 BGD of freshwater in 1995 and approximately 136 BGD of freshwater in 2000. The analysis projects that by 2030, average daily national freshwater consumption resulting from U.S. thermoelectric power generation could range from 4.7 BGD to 5.5 BGD depending upon case assumptions.

Projection of Water Needs for Carbon Capture in Thermoelectric Generation

The effects of carbon dioxide capture were estimated. For the purpose of projecting possible water needs for carbon capture, the analysis assumed that pulverized coal (PC) plants would be retrofitted with monoethanolamine (MEA) absorption for carbon capture since this technology is currently commercially available. In addition to being a water-based process and requiring more water for cooling the flue gas, CO_2 compression, and other processes; the parasitic power needed to operate the process will be about 30%. Assuming that 242 GW of scrubbed existing capacity and all new PC plants will be retrofitted, this results in the need for 73 GW of additional power to replace this lost power. If the parasitic power loss is replaced with new supercritical PC plants, freshwater withdrawal would increase by 6 billion gallons per day and consumption would increase by 4.3 billion gallons per day by 2030 compared with water use without carbon capture.

Summary of Water Needs

NETL has estimated water consumption based on the use of an evaporative cooling tower. “Consumption” represents water that must be made up to account for evaporation in the cooling tower and a relatively small amount that is consumed in unit operations within the generation process.

Table 1. Water consumed in thermoelectric generation, based on use of wet recirculating cooling tower.

Plant Type	Water Consumption Gallons/Megawatt hour electric produced
Nuclear	720
Subcritical Pulverized Coal	520
Supercritical Pulverized Coal	450
Integrated Gasification Combined Cycle	310
Natural Gas Combined Cycle	190

Table 2. Water consumed in thermoelectric generation with carbon capture, based on monoethanolamine (MEA) scrubbing to remove CO_2 and use of wet recirculating cooling tower.

Plant Type	Water Consumption with CO_2 Capture Gallons/Megawatt hour electric produced
Nuclear	720
Subcritical Pulverized Coal	990
Supercritical Pulverized Coal	840
Integrated Gasification Combined Cycle	450
Natural Gas Combined Cycle	340

RESULTS

NETL Water and Power Plants Research Program

The large amount of water required in power production, the proposed increase in electrical capacity required for the annual 2% growth in power usage in the United States, possible constraints on power production due to the requirement of carbon capture, drought conditions, and competing needs for water all point to the importance of a research program to lessen the impact of power plants on water usage. NETL is addressing the Energy/Water link in coal-based power plants with a research and development program aimed at minimizing freshwater withdrawal and consumption and any potential impacts of plant operations on water quality. NETL is a Department of Energy (DOE) National Laboratory performing and sponsering research on fossil energy, carbon sequestration, and energy efficiency and reliability. Under the Strategic Center for Coal, the Existing Plants Emissions and Capture Program is a comprehensive R&D effort focused on the development of advanced technologies to enhance the environmental performance of the existing fleet of coal-fired power plants, with application to new plants as well, including carbon capture.

The Existing Plants energy-water research is focused in the following areas: (1) advanced cooling technologies; (2) water reuse and recovery; (3) use of nontraditional sources of process and cooling water; and (4) advanced water treatment and detection technology. Four competitive solicitations have been performed, with one project awarded in 2002, five projects awarded in August 2003, seven in November 2005, and ten in July 2008. Several other projects have been funded under the Small Business Innovative Research Program (SBIR) and the University Coal Research (UCR) program. The following sections provide brief summaries of the Existing Plants R&D projects being conducted in each of the four areas.

The goal of this effort has been quantified into both a short and long term goal. The short term goal is to have technologies ready for commercial demonstration by 2015 that, when used alone or in combination, can reduce freshwater withdrawal and consumption by 50% or greater for thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost of less than $4.40 per 1000 gallons freshwater conserved. The long term goal is to have technologies ready for commercial demonstration by 2020 that when used in combination can reduce freshwater withdrawal and consumption by 70% or greater at a levelized cost of less than $2.90 per 1000 gallons freshwater conserved.

Advanced Cooling Technology

The goal of this component of the program is to improve performance and reduce costs associated with wet cooling, dry cooling, and hybrid cooling technologies. Sponsored research includes evaluation of condensing technology applied to wet evaporative cooling towers; enhancements to dry cooling; development of scale-prevention technologies and novel filtration methods in the recirculating cooling water loop; testing of an evaporative cooler that can use impaired water; testing of an environmentally safe control method to prevent zebra mussel fouling of intake structures; and development of high thermal conductivity foam to be used in air cooled steam condensers.

Use of Air2Air® Technology to Recover Fresh-Water at Thermoelectric Power Plants

SPX Cooling Technologies is evaluating the performance of its Air2Air® condensing technology in a cooling tower application on a test cell at the San Juan Generating Station (SJGS) in New Mexico. The Air2Air® uses an air-to-air heat exchanger above a wet cooling tower which takes warm, humid air from the cooling tower and contacts it with cooler, dry air from outside to condense and recover a portion of the water that just evaporated from the cooling tower. The Air2Air® system has the potential to condense as much as 20% of the cooling water that would normally be evaporated. The cooling water savings in condensed evaporate for the total United States would be 1.56 billion gallons/day if all power and industrial towers were outfitted with this technology. Pressure drop and energy use during operation will be determined, water quality will be analyzed, and potential on-site processes capable of utilizing the recovered water will be identified. A big concern is operation in freezing conditions, which makes San Juan Generating Station an ideal test site during winter due to cold temperatures. The wet/dry system will also be useful for plume abatement, and the dissipation of the plume discharged from the cooling tower fan will be studied. This project will be completed at the end of 2008.

Figure 1. Schematic of the Air2Air® condensing technology.

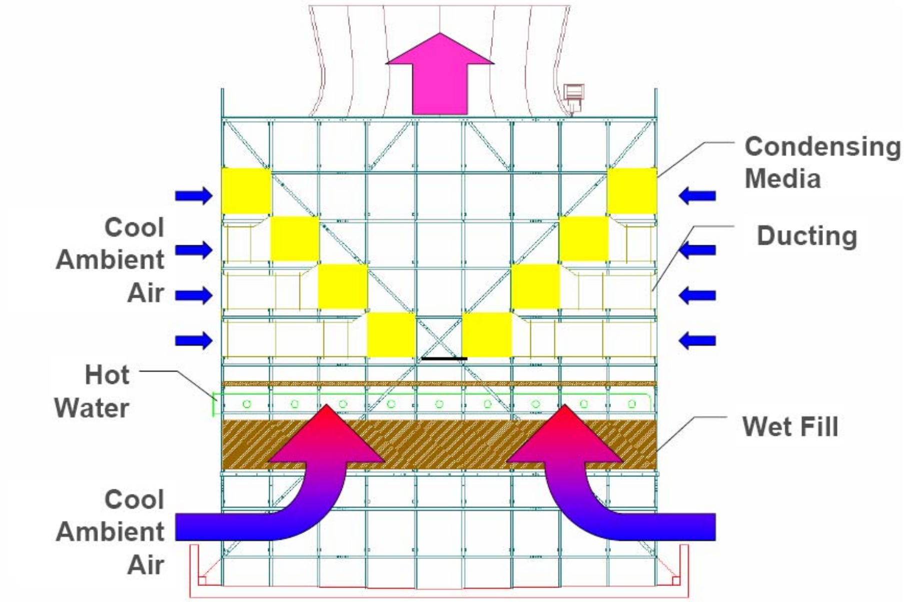

Figure 2. Photograph of the Air2Air® in operation at San Juan Generating Station. The Air2Air® is the taller stack on the left with a smaller plume.

Improvement to Air2Air® Technology to Reduce Fresh-Water Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants

SPX Cooling Technologies will further develop the Air2Air® condensing technology, enabling it to become a cost-effective and viable water-savings technology. Researchers will focus on solving issues of economy as they relate to superstructure volume, pack cost, and costly ducting details. A more efficient heat transfer pack with watertight wet path seals will also be developed.

Improved Performance of an Air Cooled Condenser (ACC) Using SPX Wind Guide Technology at Coal-Fired Thermoelectric Power Plants
SPX Cooling Technologies Inc. will improve the efficiency of power-plant air cooled condensers (ACCs) by developing wind guide technology. Wind guide technology consists of guide vanes and wind screens associated with the fans on forced draft ACCs that reduce crosswind effects by directing air towards the fan. This technology increases the flow of air in no-wind and windy conditions. Degradation of fan performance is a common problem in ACCs and results in decreased cooling performance which causes a higher backpressure in the turbine resulting in overall lower plant efficiency. Preliminary results indicate that using wind guide technology, airflow can be increased from 7% in no wind condition to 10% in a wind of 20 miles/hour. A coal-fired power unit using an ACC will be selected and the wind guide technology will be installed. Performance of the wind guide technology on the power plant will be determined by monitoring the steam temperature and pressure and condensate flow rate for the plant. Fan pressure and horsepower, and inlet/outlet air dry-bulb temperatures will be examined before and after the wind guide installation. The extent of performance gains that can be realized in both no wind and windy conditions will be determined.

Application of Pulsed Electrical Fields for Advanced Cooling in Coal-Fired Power Plants
One option for decreasing blowdown from the cooling tower is to filter out impurities rather than discharge them. Drexel University is conducting research on physical water treatment (PWT) methods that precipitate scaling ions with electrical pulses and filter them with a self-cleaning membrane. Physical water treatment uses electrical pulses to precipitate out scaling minerals. The particles can then be filtered out rather than discharging the water as blowdown. The filter will be a self-cleaning metal membrane, utilizing electrical pulses to rapidly polarize water molecules on the filter membrane such that water molecules are pulled to the membrane, pushing out the attached particles, which will then be removed by reject flow. Development of the system will be followed with validation testing. Potential benefits from this research include the ability to operate at higher cycles of concentration, which will reduce cooling tower blowdown water requirements (which also reduces the amount of freshwater make-up needed). Additional environmental benefits are expected due to the reduction in the use of chemicals for scaling and bio-fouling prevention. This project will be completed in 2009.

Application of Pulse Spark Discharges for Scale Prevention and Continuous Filtration Methods in Coal-Fired Power Plant
In this project, Drexel University will continue the development of physical water treatment (PWT) methods by continuously precipitating and removing dissolved mineral ions in cooling water. Removal of the dissolved mineral ions would allow power plants to increase the number of times that the water could be recycled before it would be discharged, which would effectively reduce the amount of makeup water needed for the

plant. It is anticipated that the technology could double the cycles of concentration thereby reducing the plant's blowdown by approximately 25 percent.

Testing of the Wet Surface Air Cooler

In conjunction with a produced water feasibility study conducted at the San Juan Generating Station (SJGS), EPRI also conducted pilot-scale testing of a wet cooling system capable of using low quality water. The wet surface air cooler (WSAC) uses a deluge system of wetted tubes and is capable of operating in a saturated mineral regime because of its spray cooling configuration. At SJGS this system was used as auxiliary cooling for condenser cooling water. The spray water was blowdown water from the existing cooling towers. Testing was performed to determine to what extent the WSAC could concentrate untreated cooling tower blowdown before thermal performance was compromised. It was also used as a pre-concentrating device for the cooling tower blowdown that is typically evaporated in a brine concentrator or evaporation pond at this zero discharge facility. The pilot test unit was skid mounted and consisted of three separate tube bundles. Each bundle was constructed of a different metal to evaluate the corrosion potential of the degraded water. The pilot unit was instrumented to monitor thermal performance, conductivity of the spray water, and corrosion. The unit was successful in increasing the cycles of concentration of the cooling water. No scaling was observed in the WSAC, however, there was a precipitation problem in other areas and a filtration method needs to be installed to use this cooling system. This project was finalized in 2006. The pilot unit was shipped back to the manufacturer, Niagara Blower, and will be used for further testing.

Environmentally-Safe Control of Zebra Mussel Fouling

Zebra mussels are small bivalves that can live in rivers and lakes in enormous densities. They can attach in great numbers to almost any hard surface. The colonization of zebra mussels on cooling water intake structures can lead to significant plant outages. There is a need for economical and environmentally safe methods for zebra mussel control where this invasive species has become problematic. Researchers with the New York State Education Department evaluated a particular strain of naturally occurring bacteria, *Pseudomonas fluorescens*, strain CL145A (Pf-CL145A), which has shown to be selectively lethal to zebra mussels but benign to non-target organisms. Testing was conducted on the house service water treatment system for Rochester Gas and Electric Corporation's Russell Station that withdraws 4 to 5 MGD from Lake Ontario.

The research suggests that this method for zebra mussel control will pose less of an environmental risk than the current use of biocides like chlorine. However, if this method is to be widely adopted, it must be cost competitive. Laboratory experiments to define key nutrients were required to produce more toxin per bacterial cell. Experiments succeeded in achieving about an 88 percent reduction in the cost of preparing the fermentation medium that is needed to produce high yields of toxic Pf-CL145A cells. This new fermentation medium, in conjunction with a revised fermentation protocol, will serve as the basis for future commercial production of large quantities of Pf-CL145A at relatively low cost. Thus, this bacterial approach to zebra mussel control has now become more economically competitive with the cost of biocides currently used by power plants. This project was finalized in 2008.

Enhanced Performance Carbon Foam Heat Exchanger for Power Plant Cooling
One of the biggest drawbacks of dry cooling is the high capital expenditure required for the much larger heat exchanger required for air cooling. Heat transfer from air to tubes/finned tubes is not efficient hence a much larger surface area is required. If the heat transfer rate could be increased, a smaller heat exchanger could be used. Ceramic Composites, Inc. has developed a high thermal conductivity foam that is formed into fins and attached to aluminum tubes for use in an air cooled condenser. A small prototype was fabricated and tested for heat transfer ability by SPX Cooling Technologies. This project was completed in 2006. Although the material slightly improved heat transfer, it is too expensive for dry cooling tower application.

Water Reuse and Recovery
The goal of this component of the program is to reuse power plant cooling water and associated waste heat and investigate methods to recover water from coal and power plant flue gas. The use of waste heat has been investigated for use in coal drying, freshwater production, and additional power production with an ammonia bottoming cycle. When coal is burned in the boiler, a significant amount of water is discharged in the flue gas from water associated with the coal, the oxidation of hydrogen in the fuel, and humidity in the combustion air. There are three basic ways to remove the water from the flue gas: (1) condense it out by cooling, (2) use a desiccant, or (3) filter it out using a membrane. The Existing Plants program is investigating all three methods.

Use of Coal Drying to Reduce Water Consumed in Pulverized Coal Power Plants
Lehigh University conducted laboratory-scale testing to evaluate the performance and economic feasibility of using low-grade power plant waste heat to partially dry low-rank coals prior to combustion in the boiler. While bituminous coals have minimal moisture content (less than 10%), low-rank coals contain significant amounts of water – subbituminous and lignite coals contain 15-30% and 25-40% respectively. In Lehigh's project, the process heat from condenser return cooling water was extracted upstream of the cooling tower in order to warm ambient air that was then used to dry the coal. Lowering the temperature of the return cooling water reduced evaporative loss in the tower, thus reducing overall water consumption. In addition, drying the coal prior to combustion can improve the plant efficiency, and in return reduce overall air emissions. Variations of this approach were also being evaluated such as using heat from combustion flue gas to supplement the condenser return cooling water to dry the coal. Lehigh's project was finalized in 2006.

Information from this project was used to design a full-scale coal drying system at the Great River Energy (GRE) 546 MW lignite-fired Coal Creek Power Station located near Underwood, North Dakota. The Coal Creek project is being funded under DOE/NETL's Clean Coal Power Initiative. There is also research being done to use a similar dryer to dry coal for off-site usage. A pilot-scale facility for beneficiation of high-moisture coals was built by GRE at Coal Creek Station. There is enough low-grade waste heat at Coal Creek Station to remove 4.2 million pounds of water from 9,100 tons/hr of lignite (83 million tons per year) using the fixed bed dryer technology. This is equivalent to the water being evaporated by the plant's cooling towers. After completion of the pilot-scale fixed bed coal dryer testing, design of a commercial unit will begin. Current expectations are that GRE would build a fixed bed coal dryer in a 100 ton/hr range (800,000 tons/yr). Vattenfall of Sweden worked with Great River Energy and Lehigh University and conducted a feasibility study and economic evaluation of a lignite dryer using air and waste nitrogen from the Air Separation Unit in a fluidized bed dryer, as an alternative to a steam dryer, in a 1,000 megawatt electric Oxyfuel plant. The lower investment cost in combination with the potential improvement in the performance could result in lower cost of electricity for an oxyfuel power plant using an air/nitrogen dryer instead of a steam dryer.

An Innovative Fresh Water Production Process for Fossil Fired Power Plants Using Energy Stored in Main Condenser Cooling Water
The University of Florida investigated a desalination technique using waste heat from the condenser that would allow power plants that use saline water for cooling to become net producers of freshwater. Saline water cools and condenses the low pressure steam and the warmed water from the condenser then passes through a diffusion tower to produce humidified air. The humidified air goes to a direct contact condenser to condense out fresh water. The capital and energy costs of this process are competitive with those of reverse osmosis or flash-evaporation technologies. Cool air, a by-product of this process, can also be used to cool nearby buildings. This project was finalized in 2006.

Water Conserving Steam Ammonia Power Cycle
A project by Energy Concepts Company is investigating the use of waste heat to operate an ammonia Rankine cycle to generate additional power. The planned test site is Kotzebue Electric Association in Kotzebue, Alaska. They plan to use the waste jacket heat from a diesel generator to produce about 150 kW of electric power. From the water conservation perspective, this system will demonstrate two ways of reducing water consumption pursuant to generating electricity. First, as much heat as possible will be put into the city water supply. This is quite helpful, as otherwise they receive it at about 45ºF, which is too cold for comfort, and costs extra heating oil to make hot water from it. That will accept about one third of the reject heat, since they can't heat the water hotter than 66ºF. Secondly, they will use air cooling, which is very effective most of the year in Alaska. Finally, and only during the summer months, they will supplement those two cooling methods with water from a cooling tower. Initially, a prototype 25 kW unit in Annapolis will be tested, replicating the conditions in Alaska. Then the full-scale unit will be installed in Kotzebue in the summer of 2009.

Recovery of Water from Boiler Flue Gas
Conducted by Lehigh University, this project will be a combination of laboratory and pilot scale experiments and computer simulations to investigate use of condensing heat exchangers to recover water from boiler flue gas at coal-fired power plants. Researchers conducted computational fluid mechanics analyses to aid in the design of the compact fin tube heat exchanger to condense water vapor from flue gas. The extent to which removal of acid vapors from flue gas and condensation of water vapor can be achieved in separate

stages of the heat exchanger system was determined via laboratory and pilot plant experiments. The technology developed will provide coal-fired utilities with a method of producing water from flue gas that would otherwise be evaporated from the stack. This water would then be available for power plant operations such as cooling tower or flue gas desulfurization make-up water. An added benefit of cooling the flue gas to remove water is the potential to remove vapor phase sulfur trioxide/sulfuric acid, and to utilize the rejected sensible and latent heat in the boiler or turbine cycle resulting in increased boiler efficiency. This project will be completed in 2008.

Recovery of Water from Boiler Flue Gas Using Condensing Heat Exchangers
Lehigh University researchers will continue to develop condensing heat-exchanger technology for coal-fired power plants for the recovery of water from flue gas. In particular, researchers will expand the database on water and acid condensation characteristics by performing slip-stream tests at two different power plants, develop cost-effective solutions to reducing acid corrosion of heat-exchanger tubes, determine condensed flue-gas water-treatment needs, and develop condensing heat-exchanger designs for full-scale applications. The successful development of cost-effective, corrosion-resistant condensing heat-exchanger systems for use in coal-fired power plants will provide opportunities to recover water from boiler flue gas.

Water Extraction from Coal-Fired Power Plant Flue Gas
The University of North Dakota's Energy & Environmental Research Center (UND EERC) developed a technology to extract water vapor from coal-fired power plant flue gases using a liquid desiccant. The flue gas is cooled, and then sent through either a spray tower or packed bed configuration where the desiccant, calcium chloride, absorbs water from the flue gas. The wet desiccant is then heated to remove the water, and the water vapor is then condensed. The original project was finalized in 2006. Ongoing research was conducted in a Jointly Sponsored Research Program with EERC. Currently, they are expanding this research to include the desiccant system and condensing heat exchangers and integrating them into a system to test carbon capture methods.

Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue Gas
Investigators at the Gas Technology Institute will develop and test a membrane-based technology to recover water and energy from power-plant flue gas. The first of two stages will recover high-purity water and energy that can be used to replace plant boiler makeup water as well as improve plant efficiency. The second stage will recover the larger portion of water that can be used for cooling tower makeup. Research will include membrane design and modeling, performance optimization and lab testing, design and fabrication of a pilot-scale unit, pilot-scale testing, and design scale-up.

Reduction of Water Use in Wet Flue Gas Desulfurization (FGD) Systems
URS Group intended to demonstrate the use of regenerative heat exchange to reduce flue gas temperature and minimize evaporative water consumption in wet FGD systems on coal-fired boilers. Researchers planned to conduct pilot-scale tests of regenerative heat exchangers to determine the reduction in FGD water consumption and assess the

resulting impact on air pollution control systems. The tests were intended to determine the impact of operation at cooler flue gas temperatures on FGD water consumption. Additionally, possible benefits due to flue gas being cooled upstream of the ESP include: control of SO_3 emissions by condensation on fly ash; improved particulate control by the electrostatic precipitator (ESP) due to reduced gas volume and lower ash resistivity; avoided costs associated with flue gas reheat or wet stacks; and potential additional reduction in mercury removal in the ESP due to operation at a cooler flue gas temperature. This project was completed in 2008. Unfortunately, the testing was not done due to an inability to obtain the regenerative heat exchanger in a timely and economical way.

Wetland Water Cooling Partnership: The Use of Restored Wetlands to Enhance Thermoelectric Power Plant Cooling and Mitigate the Demand on Surface Water Use
In this project, Applied Ecological Services will investigate the use of wetlands as a treatment method for power-plant water reuse and as tertiary treatment of wastewater treatment-plant effluent prior to use in a power plant. Specific objectives include conducting a literature review on the use of restored wetlands for water cooling and heat management by various industries, including power producers; conducting conceptual design and technical evaluation and modeling of specific cooling strategies that employ wetlands; and designing a scale model followed by field testing of restored wetland cooling-effectiveness and benefits.

Non-Traditional Sources of Process and Cooling Water
The goal of this component of the program is to develop cost-effective approaches to using lower-quality, non-traditional sources of water to supplement or replace freshwater for cooling and other power plant needs. Water quality requirements for cooling systems can be less stringent than many other applications such as drinking water supplies or agricultural applications, so opportunities exist for the utilization of lower-quality, impaired water sources. Alternative sources which have been investigated include the following: mine pool water (the water collected in underground voids resulting from mining), produced water (water produced in association with oil and natural gas extraction), municipal wastewater, cooling water blowdown, flue gas desulfurization wastewater, acid mine drainage, municipal drinking water reverse osmosis reject wastewater, ash pond effluent, and high-silica groundwater characteristic of the western U.S. Sponsored research includes analysis of the use of water from abandoned underground coal mines to supply cooling water to power plants; analysis of the use of natural gas and oil produced waters to partially meet power plant cooling water needs; development and demonstration of mine water usage to cool thermoelectric power plants; development of membrane separation and scale-inhibitor technologies to enable power plant use of impaired waters; and pilot-scale demonstration of a variety of impaired waters for cooling.

Strategies for Cooling Electric Generating Facilities Utilizing Mine Water
West Virginia University's Water Research Institute conducted a study to evaluate the technical and economic feasibility of using water from abandoned underground coal mines in the northern West Virginia and southwestern Pennsylvania region to supply

cooling water to power plants. The study included identification of available mine water reserves in the region with sufficient capacity to support power plant cooling water requirements. The study identified eight potential sites that could provide all the cooling water make-up required for a cooling tower for a 600 MW power plant. Three of the sites were further evaluated for preliminary design and cost analysis of mine pool water collection, treatment, and delivery. The cost analysis concluded that depending on site conditions and water treatment requirements, utilization of mine pool water as a source of cooling water makeup can be cost competitive with freshwater makeup systems. The study identified only one potential site for a once-through cooling water system utilizing a flooded underground mine as a heat sink. That site would be limited to the cooling water requirements of a 217 MW unit. This project was completed in 2005.

Development and Demonstration of a Modeling Framework for Assessing the Efficacy of Using Mine Water for Thermoelectric Power Generation
A 300 megawatt power plant (Beech Hollow Power Plant) has been proposed to burn coal refuse from the Champion coal refuse pile. Plans called for use of public water at 2,000 to 3,000 gallons per minute. Numerous surface and underground mines exist within six miles of the proposed power plant. Under this project, West Virginia University's National Mine Land Reclamation Center will locate, sample, and determine the flow under wet and dry weather conditions of mine discharges in the vicinity of the proposed plant. This data will be integrated with power plant water requirements and environmental considerations to design a mine water collection, treatment, and delivery system to meet the power plant's water needs. Using the data and decision-making process derived in this project, a computer-based design tool will be developed for estimating the cost of water acquisition and delivery to the power plant. The cost of mine water use by power plants will be compared to the cost of using traditional water supplies, including surface water and public water supplies. In addition, the potential environmental improvements resulting from the utilization of mine water currently contaminating area streams will be documented. This project will be completed in 2008.

Use of Produced Water in Recirculated Cooling Systems at Power Generation Facilities
EPRI evaluated the feasibility of using produced waters, a by-product of natural gas and oil extraction, to meet up to 10 percent of the make-up cooling water demand for the mechanical draft cooling towers at the 1,800 MW San Juan Generating Station (SJGS) located near Farmington, New Mexico. Two major issues are associated with this use of produced water: (1) collecting and transporting the produced water to the plant and (2) treatment of the produced water to lower the total dissolved solids (TDS) concentration. There are over 18,000 oil and gas wells in the San Juan Basin in New Mexico, where SJGS is located, that generate over 2 million gallons per day of produced water. Most of the produced water is collected in tanks at the wellhead and transported by truck to local saltwater disposal facilities. SJGS evaluated an approach for transportation of produced water to the plant site. An 11-mile pipeline would be built to gather and convey close-in production. Existing unused gas and oil pipelines would be converted to transport produced water. Produced water must be treated prior to use at the plant in order to reduce TDS to an acceptable level. The most economical treatment method found was

use of high efficiency reverse osmosis with a brine concentrator distillation unit. This project was finalized in 2006.

Advanced Separation and Chemical Scale Inhibitor Technologies for Use of Impaired Water in Power Plants

Nalco Company, in partnership with Argonne National Laboratory, is developing advanced scale control technologies to enable coal-based power plants to use impaired water in recirculating cooling systems. Novel scale inhibitor chemicals will be paired with filtering mechanisms (electrodialysis, electrodeionization, and to a lesser extent, nanofiltration) both to decrease blowdown and allow poorer quality water to be used in cooling towers. The use of impaired water is currently challenged technically and economically due to additional physical and chemical treatment requirements to address scaling, corrosion, and biofouling. Researchers will work to establish quantitative technical targets, develop scale inhibitor chemistries for high stress conditions, and determine the feasibility of membrane separation technologies to minimize scaling. Subsequently, researchers will develop selected separation processes and optimize the compatibility of technology components at the laboratory scale. Finally, integrated technologies will be tested using selected pilot scale model sites to validate the performance. If successful, the technology developed will make the use of impaired waters by coal-fired power plants more feasible. The new technologies developed have the potential to: reduce the volume of make-up water required for recirculating cooling systems; reduce the volume of water generated from cooling tower blowdown; and lower the cost of using impaired water to a point that is as cost efficient as using freshwater. This project will be completed in 2009.

An Innovative System for the Efficient and Effective Treatment of Non-traditional Waters for Reuse in Thermoelectric Power Generation

Clemson University is evaluating specifically designed pilot-scale constructed wetland systems for treatment of targeted constituents in non-traditional waters for reuse in thermoelectric power generation and other purposes. Four non-traditional waters, which included ash basin water, cooling water blowdown, flue gas desulfurization (FGD) water and produced water were obtained or simulated to measure constructed wetland treatment system performance. Based on data collected from FGD experiments, pilot-scale constructed wetland treatment systems can decrease aqueous concentrations of elements of concern (As, B, Hg, N, and Se). Percent removal was specific for each element, including ranges of 40-78% for As, 78- 98% for Hg, 44-89% for N, and no removal to 85% for Se. Other constituents of interest in final outflow samples should have aqueous characteristics sufficient for discharge, with the exception of chlorides. Based on total dissolved solids, co-management or ion reduction (e.g. reverse osmosis, nanofiltration, ultrafiltration, etc.) techniques will be needed for discharge or reuse of high ionic strength waters. Based on data collected from produced water experiments, hybrid pilot-scale constructed wetland treatment systems can decrease aqueous concentrations of elements of concern (Zn, Cd, Pb, and Cu). Percent removal was specific for each element, including ranges of 38-100% for Cd, 91- 100% for Cu, 93-99% for Pb, and 40-100% for Zn. Reuse of these waters will likely depend on the chloride concentration of the outflow samples, but with use of reverse osmosis technology, chloride concentrations may be decreased sufficiently for reuse as service water. Concentrations of arsenic, selenium, chromium, and zinc were decreased in ash basin waters by constructed wetland treatment. Average removal for arsenic, selenium, chromium, zinc, and mercury was 88, 21, 71, 68, and 94% respectively. Pilot-scale constructed wetland treatment decreased aqueous concentrations of chlorine, copper, zinc and lead in cooling waters. Average percent removals for each element were 97% for Cu, 88% for Pb, and 30% for Zn. Data from pilot-scale studies clearly indicate that constructed wetland treatment systems can remediate FGD waters, ash basin waters, cooling waters and produced waters for reuse or discharge. This project will end in 2008.

Reuse of Treated Wastewaters in the Cooling Systems of Coal-Based Power Plants
The objective of this study, conducted by the University of Pittsburgh and Carnegie Mellon University, is to assess the potential of three types of impaired waters for cooling water makeup in coal-based plants: secondary treated municipal wastewater; passively treated coal mine drainage; and ash pond effluent. To determine the feasibility of impaired water use, the following activities will be conducted: assessment of the availability and proximity of impaired waters at twelve power plant locations; assessment of regulations and permitting issues relevant to use of impaired waters; determination of general water quality of the three types of impaired waters being studied and specific water quality of impaired waters at the selected sites; construction and testing of model cooling towers; field testing of key operational parameters for the cooling system operated with the three different impaired waters; development of a mathematical model for water quality characteristics in cooling systems operated with different impaired waters; and assessment of the treatment needs for the cooling tower discharge streams. The technology developed will make use of impaired waters by coal-fired power plants more feasible by providing necessary information on geographic proximity, pretreatment requirements, available quantities, and regulatory and permitting issues. Additionally, key design and operating parameters will be determined to aid in successful use of the impaired waters without detrimental impact on cooling system performance. This project will be completed in 2009.

Use of Treated Municipal Wastewater as Power Plant Cooling System Makeup Water: Tertiary Treatment versus Expanded Chemical Regimen for Recirculating Water Quality Management
Carnegie Mellon University will provide engineering and economic data and analyses to determine optimal treatment approaches for use of wastewater treatment-plant effluent as cooling water. Investigators will evaluate the costs and benefits of implementing tertiary treatment of municipal wastewater prior to use in power plants versus chemical treatment at the power plant to manage cooling water quality. Research will include studying current use of wastewater treatment-plant effluent for power-plant makeup; conducting laboratory tests, followed by pilot-scale field tests, with wastewater treatment-plant effluent of different qualities; testing a variety of corrosion, scaling, and biofouling control methods; and performing comparative life-cycle cost and benefit analyses.

Internet-Based, GIS Catalog of Non-traditional Sources of Cooling Water for Use at America's Coal-Fired Power Plants

To reduce high-quality freshwater withdrawal and consumption for power production, Arthur Langhus Layne will create an internet-based, GIS catalog of non-traditional sources of cooling water for coal-fired power plants. Data will be developed to allow the economically beneficial use of oil and gas produced water, abandoned coal-mine water, industrial waste water, and low-quality groundwater. By pairing non-traditional water sources to power-plant water needs, the research will allow power plants that are affected by water shortages to continue to operate at full capacity without adversely affecting local communities or the environment.

Reuse of Produced Water from CO_2 Enhanced Oil Recovery, Coal-Bed Methane, and Mine Pool Water by Coal-Based Power Plants

In this project, the University of Illinois will evaluate the feasibility of reusing three types of non-traditional water sources for cooling or process water for coal-based power plants in the Illinois Basin: (1) produced water from CO_2-enhanced oil recovery, (2) coalbed methane produced water, and (3) water from active and abandoned underground coal mines. Tasks will include evaluating the quantity and quality of the produced water, investigating suitable treatment technologies, and conducting a detailed economic and benefits analysis. The research will provide critical information for the use of these non-traditional water sources for power-plant makeup water, which would allow for increased use of non-traditional waters in the Illinois Basin and nationally.

Technology to Facilitate the Use of Impaired Waters in Cooling Towers

Researchers at GE Global Research will develop a new silica-removal technology that can be used in combination with other separation technologies to make non-traditional waters available for use in evaporative cooling towers in thermoelectric power plants. Research will include material selection and synthesis; material recycle and bench-top demonstration; and design engineering, scale-up, and pilot demonstration. Results are expected to allow for the economical use of many impaired waters that are currently too expensive to treat with current technology.

Advanced Water Treatment and Detection Technology

Controls on the emission of mercury (Hg) and possibly other trace elements have raised concerns about the ultimate fate of these contaminants once they are removed from the flue gas. Preventing these "air pollutants" from being transferred to surface or ground waters will be critical. In addition, ammonia from selective catalytic reduction systems used to control nitrogen oxide emissions can appear in a power plant's wastewater streams. Sponsored research includes study of the fate of arsenic (As), selenium (Se), and Hg in a passive integrated treatment system for fossil plant waste water; demonstration of a market-based approach to abandoned mine land reclamation by creating marketable water quality and carbon emission credits; utilization of anionic clay sorbents for treating and reusing power plant effluent; and evaluation of wetland use to treat plant scrubber wastewater.

Fate of As, Se, and Hg in a Passive Integrated System for Treatment of Fossil Plant Waste Water

Mercury, arsenic, and selenium are pollutants often present at trace-levels in power plant flue gas and wastewater. In addition, ammonia "slip" from selective catalytic reduction systems (SCRs) for reduction of NOx emissions can appear in wastewater streams such as FGD effluents and ash sluice water. TVA and EPRI are conducting a three-year study of a passive treatment technology to remove trace levels of As, Se, and Hg as well as ammonia and nitrate from fossil power plant wastewater at the Paradise Fossil Plant near Drakesboro, Kentucky. NETL funded the construction of an extraction trench containing zero-valent iron for the removal of these trace compounds. The wetlands are being used for denitrification. This project was completed in 2006.

Demonstrating a Market-Based Approach to the Reclamation of Mined Lands in West Virginia

EPRI demonstrated a market-based approach to abandoned mine land (AML) reclamation by creating marketable water quality and carbon emission credits. The project involved the reclamation of thirty acres of AML in West Virginia through installation of a passive system to treat acid mine drainage. Water quality was measured and conventional economic principals were used to develop the costs and environmental benefits of the remedial treatments. Potential environmental credits considered included water quality credits due to decreased acid mine drainage and other benefits resulting from the soil amendment, as well as potential credits at other sites for CO_2 sequestration. This project was finalized in 2006.

Novel Anionic Clay Adsorbents for Boiler-Blow Down Waters Reclaim and Reuse

The University of Southern California is studying the utilization of novel anionic clay sorbents for treating and reusing power plant effluents. Concerns exist about heavy metals, such as Hg, As and Se, that can be found at low levels in power plant effluents. Since the waste stream flow rates are high and the metals concentrations are at trace levels, it is difficult to effectively clean the water. As a result, highly efficient treatment techniques are required. The University of Southern California is applying novel sorbents to treat, recycle, and reuse boiler blow-down streams. The goal of this project is to develop an inexpensive clay-based sorbent that could be used to treat high-volume, low-concentration wastewater containing arsenic and selenium. This project will be completed in 2009.

Specifically Designed Constructed Wetlands: A Novel Treatment Approach for Scrubber Wastewater

Clemson University evaluated specifically designed pilot-scale constructed wetland treatment systems for treatment of targeted constituents in coal-fired power plant FGD wastewater. The overall objective of this project was to decrease targeted constituents, Hg, Se, and As concentrations, in FGD wastewater to achieve discharge limitations established by the Clean Water Act. Specific objectives of this research were: (1) to measure performance of this treatment system in terms of decreases in targeted constituents (Hg, Se and As) in the FGD wastewater; (2) to determine how the observed performance is achieved (both reactions and rates); and (3) to also measure performance in terms of decreased bioavailability of these elements (i.e. toxicity of sediments in constructed wetlands and toxicity of outflow waters from the treatment system). Performance of the pilot constructed wetland treatment systems at the final stage indicated that the system was decreasing aqueous concentrations of the targeted wastewater constituents (As, Hg, and Se) for the majority of the wastewaters. This project ended in 2005.

CONCLUSIONS

Freshwater resources and reliable and secure electrical energy are inextricably linked. Thermoelectric generation requires a sustainable, abundant, and predictable source of water and is second only to irrigation as the largest user of freshwater in the United States. As the demand for electricity increases, so will the need for water for power generation. However, thermoelectric power plants will increasingly compete with demands for freshwater by the domestic, commercial, agricultural, industrial, and in-stream use sectors. In addition, current and future water-related environmental regulations and requirements will continue to challenge power plant operations. As such, there will be increasing pressure to retire existing plants and deny permits for new power plants due to water availability and quality issues.

In response to this challenge to national energy sustainability and security, DOE/NETL is carrying out an R&D program focused on the development and application of advanced technologies and concepts to better manage how power plants use and impact freshwater. It is anticipated that this research will help to alleviate potential conflicts between growing demands for electricity and increasing pressures on the nation's freshwater resources.

REFERENCES

Water Requirements for Existing and Emerging Thermoelectric Plant Technologies DOE/NETL-402/080108, August 2008
http://www.netl.doe.gov/energy-analyses/pubs/Water%20Benefits%20Primer_09_02_08.pdf

Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements *2008 Update* DOE/NETL-400/2008/1339
http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/2008_Water_Needs_Analysis-Final_10-2-2008.pdf

Reports on DOE/NETL's power plant water R&D activities located at
http://www.netl.doe.gov/technologies/coalpower/ewr/water/index.html